A Xylophone Configuration for a third Generation Gravitational Wave Detector

Stefan Hild,* Simon Chelkowski, and Andreas Freise
School of Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK

Janyce Franc, Nazario Morgado, and Raffaele Flaminio
Laboratoire des Materiaux Avances (LMA), 22 Boulevard Niels Bohr, Villeurbanne Cedex, 69622, France

Riccardo DeSalvo
California Institute of Technology, LIGO Project, Pasadena, CA 91125, USA
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Achieving the demanding sensitivity and bandwidth, envisaged for third generation gravitational wave (GW) observatories, is extremely challenging with a single broadband interferometer. Very high optical powers (Megawatts) are required to reduce the quantum noise contribution at high frequencies, while the interferometer mirrors have to be cooled to cryogenic temperatures in order to reduce thermal noise sources at low frequencies. To resolve this potential conflict of cryogenic test masses with high thermal load, we present a conceptual design for a 2-band xylophone configuration for a third generation GW observatory, composed of a high-power, high-frequency interferometer and a cryogenic low-power, low-frequency instrument. Featuring inspiral ranges of 3200 Mpc and 38000 Mpc for binary neutron stars and binary black holes coalesences, respectively, we find that the potential sensitivity of xylophone configurations can be significantly wider and better than what is possible in a single broadband interferometer.

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I. INTRODUCTION

Over the last decades scientists pioneered the field of laser-interferometric gravitational wave (GW) detection, culminating in the establishment of a worldwide network of large-scale gravitational wave detectors [1, 2, 3].

The design and construction of a second generation of GW observatories is well underway and observation with ten times improved sensitivity is expected to start in about 5 years [4, 5, 6]. Triggered by the Einstein GW Telescope (ET) design study within the European FP7 framework [7], research has started on design options for a third generation GW observatory [9, 10], aiming for a sensitivity 100 times better than of current instruments and thus allowing us to scan a one million times larger fraction of the Universe for astrophysical GW sources. In addition to improved sensitivity, a key feature of observatories such as ET will be their strongly expanded bandwidth, covering the range from 1 Hz to 10 kHz. Especially the extension of the detection band towards the lower frequency end will increase the number and signal-to-noise ratio of observable gravitational wave signals and therefore significantly enhance the astrophysical impact of third generation observatories [8].

As we will show in Section II, for achieving the immense bandwidth envisaged for instruments such as ET, it might be highly beneficial, if not even technically unavoidable to split the detection band into several optimized detectors of moderate bandwidth, forming altogether a so-called *Xylophone* interferometer covering the full detection band. In Section III we present for the first time a potential design for a third generation xylophone configuration, consisting of a low-power, cryogenic interferometer optimized for the low-frequency band and a higher-power, room-temperature interferometer covering the high-frequency band.

II. POTENTIAL BENEFITS OF XYLOPHONE CONFIGURATIONS FOR THIRD GENERATION GRAVITATIONAL WAVE DETECTORS

Spanning the detection band over four orders of magnitude in frequency, as it is ask for third generation GW observatories such as ET, is technically extremely challenging: Different noise types dominate the various frequency bands and often show opposite response for different tuning of the same design parameter.

A well-known example for such a behavior is the correlation of the two quantum noise components: photon shot noise (PSN) and photon radiation pressure noise (PRPN). In order to improve the PSN limited sensitivity at high frequencies one needs to increase circulating optical power of the GW detector, which at the same increases the PRPN and therefore worsens the low frequency sensitivity. Vice versa, lowering the circulating power reduces the PRPN and improves the low frequency sensitivity, while the PSN contribution will raise and reduce the high frequency sensitivity.

This dilemma can be resolved by following the path of electromagnetic astronomy, where telescopes are built for a specific, rather narrow-banded detection window

*Electronic address: hild@star.sr.bham.ac.uk

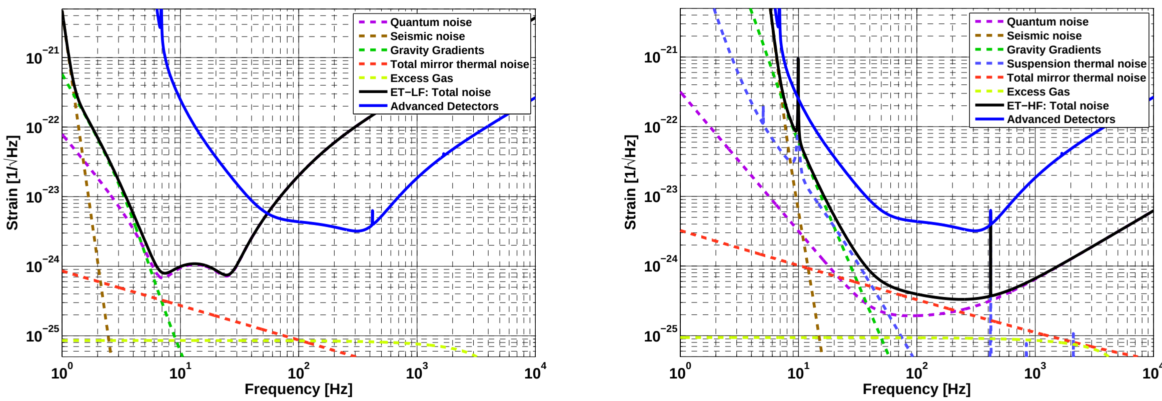

FIG. 1: Fundamental noise contributions of the two analysed xylophone detectors. While the high frequency interferometer, ET-HF, (right plot) features a circulating light power of 3 MW, the low-frequency detector, ET-LF, (left plot) operates with only 18 kW of circulating power, allowing easier use of cryogenic test masses. The main parameters of both interferometers are compared in Table I. As a comparison, the sensitivity curve of the 'Advanced' detectors is shown in blue.

(visible, infrared etc) and later on the data from different frequency bands is combined to cover the desired bandwidth. Building two or more GW detectors, each optimised for reducing the noise sources at one specific frequency band, can form a xylophone observatory providing substantially improved broadband sensitivity.

The xylophone concept was first suggested for Advanced LIGO, proposing to complement the standard broadband interferometers with an interferometer optimized for lower frequency, thus enhancing the detection of high-mass binary systems [11, 12, 13]. The concept was then taken forward for underground observatories [14]. In this article we extend the xylophone concept for the application in third generation GW observatories.

One may think that a xylophone might significantly increase the required hardware and its cost, i.e. building more than one broadband instrument. However, such an argument does not take the technical simplifications that it would allow, the better reliability of simpler instruments, and the more extensive scientific reach allowable into account. For example splitting a third generation observatory in to a low-power, low-frequency and a high-power high-frequency interferometer, has not only the potential to resolve the above mentioned conflict of PSN and PRPN, but also allows to avoid the combination of high optical power and cryogenic test masses. To reduce thermal noise to an acceptable level in the low frequency band, it is expected that cryogenic suspensions and test masses are required. Even though tiny, the residual absorption of the dielectric mirror coatings deposits a significant amount of heat in the mirrors, which is difficult to extract, without spoiling the performance of the seismic isolation systems, and thus limiting the maximum circulating power of a cryogenic interferometer.

III. EXAMPLE OF A 2-BAND XYLOPHONE CONFIGURATION FOR THE EINSTEIN GW TELESCOPE (ET)

Starting from the single-detector ET configuration described in [10] we developed a 2-band xylophone detector configuration to resolve the high-power low-temperature problem of a single band ET observatory. Table I gives a brief overview of the main parameters of the analysed low-frequency (ET-LF) and high-frequency (ET-HF) detector.

A. ET-HF detector

The high-frequency interferometer, ET-HF, is an upscaled but otherwise only moderately advanced version of a second generation interferometer: We considered an arm length of 10 km and a circulating light power of 3 MW. In order to achieve the aimed high frequency sensitivity we also assumed the implementation of squeezed light [16] as well as tuned signal recycling (SR) [15], which allows to simultaneously extract both signal sidebands.

To reduce the thermal noise contributions, limiting the medium frequency range, without recurring to cryogenic temperatures we considered increasing the beam size to the technical maximal feasible value of about 12 cm beam radius, as well as changing the beam shape from the currently used TEM_{00} to mesa beams [17] or a higher order Laguerre Gauss (LG) mode [18, 19]. Using the LG_{33} mode the coating Brownian and the substrate Brownian noise are reduced by factors 1.61 and 1.40, respectively [20]. Please note that the suspension system of ET-HF is identical to a second generation GW observatory, but scaled up to cope with the higher mirror mass of 200 kg, required to manage the larger beams with a feasible mirror aspect ratio [21]. The sensitivity curve and the noise

Parameter	ET-HF	ET-LF
Arm length	10 km	10 km
Input power (after IMC)	500 W	3 W
Arm power	3 MW	18 kW
Temperature	290 K	10 K
Mirror material	Fused Silica	Silicon
Mirror diameter / thickness	62 cm / 30 cm	62 cm / 30 cm
Mirror masses	200 kg	211 kg
Laser wavelength	1064 nm	1550 nm
SR-phase	tuned (0.0)	detuned (0.6)
SR transmittance	10 %	20 %
Quantum noise suppression	10 dB	10 dB
Beam shape	LG_{33}	TEM_{00}
Beam radius	7.25 cm	12 cm
Clipping loss	1.6 ppm	1.6 ppm
Suspension	Superattenuator	5 × 10 m
Seismic (for $f > 1$ Hz)	$1 \cdot 10^{-7}$ m/f^2	$5 \cdot 10^{-9}$ m/f^2
Gravity gradient subtraction	none	factor 50

TABLE I: Summary of the most important parameters of the 2-band xylophone detector shown in Figure 1 .

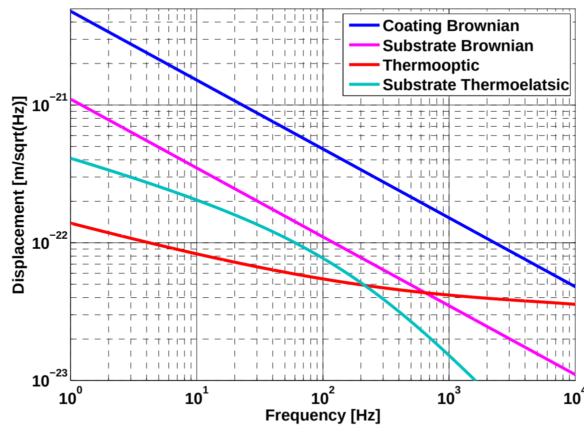

FIG. 2: Apparent displacement from individual thermal noise contributions for a single cryogenic silicon test mass of ET-LF.

budget of ET-HF is shown in the right hand plot of Figure 1.

B. ET-LF detector

Unlike ET-HF the low frequency xylophone interferometer, ET-LF, will require several innovative techniques, well beyond the scope of first and second generation GW interferometers. In order to reduce seismic noise, we assumed an extremely long suspension system, composed of 5 stages, each 10 m tall, in addition to the reduced seismic level of an underground location [22]. Even though the reduced seismic excitation of an underground site decreases the gravity gradient noise significantly, a further reduction of a factor 50 is required from subtraction of gravity gradient noise.

The main feature of the LF detector is that all thermal noise sources are significantly reduced by using cryogenic test masses, which is made possible by the reduced optical power of only 18 kW, comparable to that of a first generation GW detector. Sapphire [23] and silicon have been proposed as test mass material for a cryogenic GW detector. However, material costs and material properties, as well as the available boule dimensions [28] seem to slightly favor silicon. Therefore, we considered silicon test masses cooled to a temperature of 10 K in this article. The most important material parameters used in our analysis are the Youngs modulus of 10 K Silicon of 164 GPa and the loss angles of $5 \cdot 10^{-5}$ and $2 \cdot 10^{-4}$ for the low and high refraction coating materials, respectively.

Unfortunately the available measurements indicate higher loss angles for the coating materials at cryogenic temperatures than at room temperature [26]. However, since research on cryogenic coatings just started, we optimistically assumed [29] that by the time construction of third generation instruments starts, coatings will be available featuring the same loss angles as current coatings at room temperature [24, 25]. The resulting thermal noise contributions of a single cryogenic silicon test mass are shown in Figure 2.

Using silicon mirrors also implies to change the laser wavelength from 1064 nm to 1550 nm where Silicon is highly transmissive and has very low absorption [27]. Changing the laser wavelength has an impact on coating Brownian noise and quantum noise. Due to the fact that for 1550 nm light the mirror coatings have to be about 1.5 times thicker [30], the overall coating Brownian noise is increased by a factor $\sqrt{(1550/1064)} = 1.2$. In addition the PSN is also increased by a factor 1.2, while the PRPN is improved by a factor 1.2.

The resulting noise buget of ET-LF, limited by gravity gradient noise at low frequencies and quantum noise at all other frequencies, is shown in the left hand plot of Figure 1. Please note that we omitted suspension thermal noise from our analysis of ET-LF, as this is subject of ongoing research and so far no mature noise estimate exists. However, it appears likely that the low loss characteristics of crystalline fibers at low temperature may not be a limitation above the gravity gradient level.

C. Projected sensitivity of the xylophone configuration

The overall strain sensitivity of the proposed xylophone configuration is shown in Figure 3 and compared to the sensitivity of the single broadband ET described in [10]. The resulting inspiral ranges [31] of the xylophone are with 3200 Mpc and 38000 Mpc for binary neutron stars (BNS) and binary black holes (BBH), respectively, significantly larger than the ones for the ET single configuration (BNS range = 2650 Mpc, BBH range = 25000 Mpc). The sensitivity of the xylophone in the

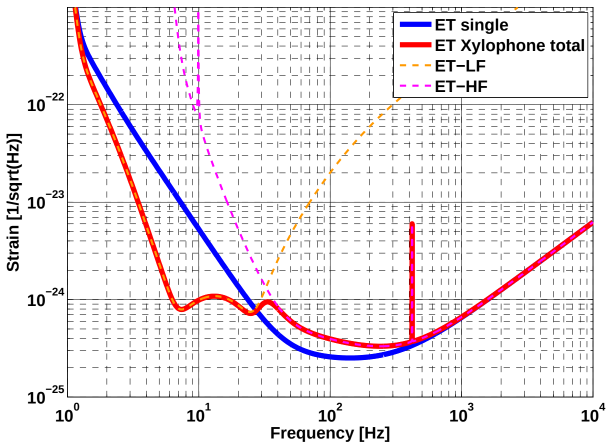

FIG. 3: Strain sensitivities of the two presented xylophone detectors (ET-LF and ET-HF) and the resulting total instruments sensitivity (ET xylophone total) in comparison to the sensitivity of the broadband ET interferometer (ET single) from [10]. (Please note that no contributions from suspension thermal noise are included for ET single and ET-LF.)

intermediate frequency range (50 to 300 Hz) is slightly worse than the one of ET-single, but the overall inspiral ranges improve due to the strongly increased sensitivity around 10 Hz. While the ET-single interferometer is limited by RPN between 2 and 30 Hz, ET-LF can make use of a narrow-band detuned signal recycling to further decrease the quantum noise.

IV. SUMMARY AND OUTLOOK

We presented an initial design of a xylophone interferometer for a third generation GW observatory, composed of a high-power, high-frequency interferometer complemented by a cryogenic low-power, low-frequency interferometer. The xylophone concept provides a feasible alternative (decoupling the requirements of high-power laser beams and cryogenic mirror cooling) compared to a single broadband interferometer (ET-single) and is found to potentially give significantly improved senstivity.

Future efforts will focus on investigating the prospects of additional xylophone interferometer either to improve the peak sensitivity around 100 Hz or to push the low frequency wall further down in frequency.

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[28] It seems for sure that in a few years silicon boules with a diameter of 45 cm will be available. It is not clear whether by the time of ET construction the here considered diameter of 62 cm will be available. However, even in case ET-LF would be constructed with silicon test masses of only 45 cm diameter, the coating Brownian noise would only be increased by a factor $62/45 = 1.38$, which would not significantly change the sensitivity of ET-LF (see Figure 1)
[29] Please note that even in case the loss angles of cryogenic coatings cannot be improved in future, the total mirror thermal noise trace in Figure 1 would only increase by about a factor of 2, yielding only a very minor decrease of the ET-LF sensitivity.
[30] This assumes coating materials with the same index of refraction as used for a wavelength of 1064 nm.
[31] We considered NS of 1.4 solar masses and BH of 30 solar

masses. The inspiral ranges are calculated for averaged sky location and a snr of 8.